

SOLID STATE ELECTRIC GENERATOR USING RADIONUCLIDE-INDUCED
EXCITON PRODUCTION

BACKGROUND OF THE INVENTION

The present application is based on U.S. provisional application S.N. 60/071,667 filed on January 16, 1998 and priority therefrom is claimed under 35 U.S.C. § 120. The
5 entire content of Provisional Application S.N. 60/071,667 is incorporated herein by reference.

A wide variety of commercial and scientific equipment requires a reliable source of electrical power, either stored or generated, for operation in remote locations not connected
10 to electrical power distribution networks. Some of the known terrestrial uses for such power sources include transmitters, relays, boosters, unmanned weather stations, environmental monitoring stations, radar arrays in antarctic/arctic/ other remote areas, submarine cable boosters and the like. Aerospace
15 and outerspace applications are even more in need of reliable sources of electrical power. Chemical batteries are well known sources of stored power but often cannot provide sufficient stored energy and power to meet mission needs. In such cases, batteries must be supplemented by solar or other energy
20 conversion devices.

Conventional schemes, such as the solid state contact potential difference (SSCPD) cell, have been proposed as an energy conversion device. For example, in "Radioisotopic Energy Conversion Utilizing a Solid-State Contact Potential Difference Cell", Paul Brown, IsoGen Inc, Oregon City, OR97045, U.S.A. published in p. 439-450 of the Proceedings of the 12th Symposium on Space Nuclear Power and Propulsion, Albuquerque, New Mexico, U.S.A. organized by the American Institute of Physics, 1995 CONF 950110.) which relied on silicon. Such concepts as the SSCPD could perhaps be made with diamond semiconductor but have an intrinsically low voltage derived from the contact potential of dissimilar metals (as well as for other reasons). Other schemes such as thermoelectric generation of electricity rely on conversion technology such as Stirling, AMTEC and thermovoltaic cells that rely on low band gap semiconductor material such as GaSb. (ref. Proceedings of the First NREL Conference on Thermophotovoltaic Generation of Electricity, ISBN 1-56396-353-1) Development of these technologies is based on the expectation of two to three times the efficiency of thermocouple dependent Plutonium heat sourced Radioisotopic Thermal Generators (RTGs) as seen on some interplanetary spacecraft. Any of the candidate technologies has to demonstrate performance advantages including minimal system mass and long life. Low temperature systems such as

thermovoltaic cells suffer from the need for waste heat radiators that are much larger than high temperature devices require. Stirling and AMTEC technologies pose lifetime questions for the moving parts or aggressive fluids. Finally, 5 plutonium based Radioisotopic Thermal Generators (RTG), that have been used in space, are to be phased out due to economic and environmental concerns.

Accordingly, it is an object of the present invention to provide an electrical power and heat source that offers a 10 minimal system mass.

It is a further object of the present invention to provide an electrical power and heat source whose operation is simple, compact, safe, robust and reliable.

It is yet another object of the present invention to 15 provide an electrical power and heat source that offers an electric power to mass ratio and a relatively high operating temperature that permit the use of the power source in a wide variety of spacecraft and planetary surface systems.

It also is an object of the present invention to provide 20 an electrical power and heat source that relies upon RADIONUCLIDE materials but offers minimal risk for a release of hazardous radioactive materials.

SUMMARY OF THE INVENTION

The present invention concerns an energy storage and conversion method and apparatus for providing electric and thermal power by employing several physical characteristics of thin crystalline films or plates made from wide band-gap materials, including the ability of such materials to store an isotope that emits decay energy. Beta or alpha particles may provide the primary energy source. However, other nuclear emissions such as neutrons or gamma ray photons may also be used in combination with compatible crystalline energy conversion material. The nuclear particles interact with the crystal atom electrons by a variety of mechanisms and generate a bound electron-hole pair that, when recombination occurs, yields a photon. An important photon production mechanism is the EXCITON mechanism, but by recombination in direct band gap materials, color centers, defects and vacancy mechanisms also play an important role. The photon that results from the electron-hole recombination or fluorescence may be converted to electrical energy.

In particular, the preferred embodiment of the present invention concerns the combination of diamond as a storage medium and a radioactive isotope, which is impregnated into the diamond crystalline structure so that the interstitial voids between the carbon atoms of the diamond structure are each

occupied by an atom of the radioactive isotope. However, other wide band-gap materials, such as the typical wide band-gap direct transition materials that include silicon carbide (SiC), gallium nitride (GaN), and aluminum nitride (AlN), also can be used. These materials photoluminesce at different wavelengths, e.g., SiC at about 443nm, GaN at about 388 nm, and AlN at about 200nm. Diamond, which photoluminesces at 235nm or 242nm is selected to illustrate the basic concept of the present invention. The invention relies upon the use of any one of a number of luminescent mechanisms by which crystal lattices produce electromagnetic radiation in response to charged particle irradiation, e.g., the EXCITON mechanism or emission due to color centers, defects or vacancies effect to provide a conversion of the emitted particles to photons, which subsequently are converted to electrical energy. When diamond is used as the isotope storage medium, the resulting diamond-EXCITON radioisotope generator (DEXRG) will consist of one or more stacks of diamond film. The choice of diamond is based on its physical properties of very high thermal conductivity, self annealing at elevated temperatures that will be experienced in the application described here, transmission of UV photons and chemical resistance. The possibility of an optimization of EXCITON characteristics by the stress induced into the crystal

matrix by the interstitial void filling isotopes also may be attractive.

The present invention also concerns the method of producing a DEXRG device, which includes the step of manufacturing diamond film by means of chemical vapor deposition (CVD) techniques. Then, the diamond film is processed, preferably by means of a forced diffusion process, to impregnate radioactive isotopes such as tritium or krypton-85 into the diamond interstitial voids and crystal boundaries.

10 The diamond material may be stressed in a manner that could enhance its performance as a direct band-gap material. The radioactive diamond film is then assembled into layers to achieve a mass concentration of radioactive isotope that satisfies a beginning of life specified stored energy. Next,

15 photovoltaic cells are installed in any of a number of optional configurations so that the photons released due to the EXCITON process will be efficiently converted into electrons and gathered to achieve a desired voltage and current. Finally, the device is sealed in a manner that will prevent radioactive

20 leakage but to permit access to the generated electrical energy.

Reflective materials can be applied to the assembled film stack in order to trap the emitted photons and increase the

likelihood of their passage through the photovoltaic cells. The use of phosphors or wavelength shifting media to convert the emitted UV to a frequency better suited to the available photovoltaic cells in use is also a design option.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic illustration of a sandwich of two photovoltaic cells and a diamond crystal, the diamond's matrix having tritium atoms bound in its crystal lattice which together generate nuclear (beta) particles, resulting in the
10 generation of electron hole pairs and the generation of photons from those pairs.

Figure 2 is a schematic illustration of the process of producing an apparatus that embodies the present invention.

Figures 3a-3c are illustrations of alternative
15 configurations for mounting photocells onto the apparatus.

Figure 4 is an illustration of a final packaged apparatus embodying the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The energy storage and conversion apparatus that embodies
20 the present invention comprises a storage medium, which preferably are thin crystalline films or plates made from wide band-gap materials that have the ability to store an isotope

that emits decay energy. The apparatus also includes a primary energy source, which preferably is an isotope that emits beta or alpha particles, and may even emit other nuclear emissions such as neutrons or gamma particles. In any event, the storage
5 medium also must be able to convert the energy of the emitted particles into photons, preferably using the highly efficient EXCITON mechanism. A further important structure is a photocell or other medium for photovoltaic conversion of the energy of the emitted photons into electrical energy. Finally,
10 the structural features involved in optimizing the capture of emitted particles and photons, for interconnecting several similar structures into an operative device, and for packaging the device to ensure handling and safety, are important to the invention.

15 In a preferred embodiment, the present invention concerns the combination of diamond or other crystalline high band-gap materials as a storage medium and a radioactive isotope, which is impregnated into the crystalline structure of the diamond so that the interstitial voids between the carbon atoms of the
20 crystalline structure are each occupied by an atom of the radioactive isotope. The isotope, which may be atomic or molecular hydrogen, atomic or molecular tritium, krypton, particularly krypton-85, are loaded at densities of 100ppm to 1,500,000 ppm. The crystalline structure may be single or

polycrystalline. Both SiC and GaN are used as blue diode material and, thus, are direct band-gap materials. (The beta phase of SiC has a band gap of about 3 eV that is direct and used for the blue diode; see Gielisse, Wide band gap Electronic
5 Materials at p 409.) These materials are pure enough so that they will not have to be doped to make them sources of blue light. The invention relies upon one or more of a variety of mechanisms (e.g., the EXCITON mechanism, color centers, defects or vacancies) to provide a conversion of the emitted particles
10 to photons, which subsequently are converted to electrical energy by photocells.

Given the need for a long term source of electrical energy, the basic nuclear energy source must have a long radioactive half life that is compatible with the lifetimes of
15 devices that would embody the present invention. The half life for tritium and krypton-85 is 13 - 10.7 years, respectively, which makes both of these materials desirable. Not only does the energy source last the lifetime of a practical device, it also has a corresponding environmental and disposal advantage,
20 as about a 10 half-life period (time required for the activity to decay to one thousandth of its peak value) is just 130 years (107 for Kr-85) while for Pu-238, the ten T 1/2 times is 877 years. As between the two, tritium has an advantage over Kr-85 (and over most other nuclear decays) of being totally free

from accompanying gamma radiation during decay, and of decaying to a stable isotope (i.e., no radiation due to the decay of an excited daughter product). Further, these isotopes are compatible with diamond as a storage medium, as their size and processability provide particular advantages in achieving the DEXRG as an energy storage and conversion scheme for electric and thermal power. Also, as to tritium, it decays to Helium-3, which is chemically inert, stable and non-toxic. Diamond has the advantage that it is a naturally occurring, non-toxic material that has an atomic weight that provides a low mass and, in the event of combustion, forms innocuous gases already present in the atmosphere (i.e., CO, CO₂). The same is true of GaN, SiC, etc., although with different combustion products.

The choice of diamond is based on its physical properties, including its very high thermal conductivity, its ability for self annealing at elevated temperatures, its ability to transmit UV photons and its chemical resistance. There also is the possible enhancement of available EXCITON characteristics by the stress induced into the crystal matrix by the interstitial void filling isotopes. Diamond has a crystalline structure that permits the interstitial voids between the carbon atoms of the diamond structure to be occupied by an atom of the radioactive isotope. While other wide band-gap materials may be used that are suited to take advantage of the

physical characteristics of thin films and thin plates that are desirable in making the present invention, diamond is preferred. The choice of diamond over other material with a high hydrogen packing density, such as hydrocarbons or palladium, results from a consideration of the above issues, most important of which is the EXCITON phenomenon and the realization that diamond meets all criteria. Diamond even anneals away crystal lattice point defects (but not planar or volume defects) at the operating temperatures and thus retains its high fluorescence production efficiency. In short, diamond is superior to any other semiconducting media.

While there is a preference for diamond, based on certain fundamental requirements for the storage medium for the radioisotope, other crystalline materials also may be used. For example, it is known that the interstitial trapping of hydrogen is feasible in crystal structures in general. Additionally, the termination of surface bonds by hydrogen can occur where covalent bonds between the surface atoms and hydrogen is possible. Thus, the use of both interstitial trapping and surface bonding of hydrogen are mechanisms that can be used with crystals in general. There are instances in which it would be advantageous to use different crystals. For example, diamond is an indirect band-gap material and, as subsequently explained, the only means of generating photons

from diamond are through EXCITON emission and emission from crystal defects. In some cases, the photon production efficiency and/or photon wavelength may not provide the best match for the available photovoltaic cells. In this case it might be useful to use direct band-gap crystals such as gallium nitride or silicon carbide to store the tritium. A direct band-gap crystal can produce photons by direct excitation of the electron from the valence band into the conduction band and its subsequent decay back to the valence band. This photon production mechanism is very efficient (e.g., the mechanism responsible for light emitting diodes and semiconductor lasers). In the case of a gallium nitride crystal which stores the tritium, the photon energy emitted will be about 3.2 eV. This photon energy can be transported to photovoltaic cells made of silicon carbide that have a band-gap of 2.7 eV. This combination matches up very well. The intrinsic efficiency of the photovoltaic cell is equal to the band-gap energy of the photovoltaic cell divided by the photon energy (provided this energy is greater than or equal to the band-gap energy of the photovoltaic cell). Thus one could achieve an energy conversion efficiency with the combination of a gallium nitride photon source and a silicon carbide photovoltaic cell of $(2.7/3.2) \times 100 = 84.4\%$.

The construction of a diamond-EXCITON radioisotope generator (DEXRG) consists of one or more stacks of diamond film manufactured by means of well known chemical vapor deposition (CVD) techniques which are commercially accessible through CVD foundry facilities. As seen in Fig. 2, the silicon substrate wafers are readily available from the silicon industry and, using methane as a source gas, polycrystalline diamond film may be grown on a silicon substrate by conventional methods well known in the art. These films can be removed from the substrate using known industry techniques that depend upon relative thermal expansion coefficients and can then be cut and trimmed to a final size with high precision. Cut diamond films can be commercially purchased from vendors, such as Norton Diamond Film and DeBeers.

The method of diamond film growth will be determined by the specification established for the optimum storage of the RADIONUCLIDE isotope or mix of the two isotopes discussed. For example, conventional microwave or filament CVD growth of diamond film (which currently permit realization of films having a diameter of 12 inches and a thickness of up to 1mm) will maximize crystal grain size and thereby minimize isotope atom trap locations in the inter-crystal grain boundaries that are not as stable as the interstitial void in the case of krypton. It may be possible to use diamond growth methods such

as laser CVD that grow high quality nanometer sized crystallites in diamond films. By the laser CVD method both surface sites and interstitial sites can be maximized. All CVD processes have common features, the gas, the substrate, and an energy source. A laser is the energy source for laser assisted CVD. Since the laser is pulsed, the diamond growth phase occurs for a short time. Nanometer sized crystals of diamond are nucleated and are formed into polycrystalline films. (A reference for this process is: M.C. Polo, J. Cifre, G. Sanchez, P. Aguiar, M. Varela, J. Esteve, "Growth of diamond by laser ablation of graphite, "Diamond and Related Materials, 4, 780-783, 1995).

With nanometer sized diamond crystals, surface density, that is the total surface area of crystal grains within a given volume of diamond film, is greatly increased. The number of total available hydrogen isotope storage sites is a combination of the surface sites and the interstitial sites. By using polycrystalline films with nanophase grain sizes, the available surface area is very large and hence the number of available surface sites approaches the number of available interstitial sites. As the grain size increases, the number of available surface sites decreases. The efficiency or completeness and time required for forced diffusion of the radionuclide atoms to the center of each grain with a typical diameter of a few

nanometers is minimized and thus hydrogen concentration can be maximized. Straightforward experimental work will permit quantification of the optimum crystalline size for hydrogen concentration, but it is expected that crystal sizes as small as 1nm to single crystal devices can be used. Diamond quality is an important determinant of overall DEXRG power cell device performance. The specification of diamond film quality is concerned with the maximization of radionuclide entrapment. The two radionuclides that are preferred for DEXRG implementation will impose different sets of requirement on the relative importance of crystal surface and interstitial sites. Isotopes of hydrogen can use surface sites due to chemical covalent C-H bonds. Krypton atoms can only be permanently captured in the interstitial sites. A SIMS measurement on a sample that was subject to an 8-hour forced diffusion processing time shows that krypton trapping is stable with time, even when the sample has a net mass decrease.

Diamond crystal surface sites offer stable storage of hydrogen. Chemically, C-H bonds are very strong (99 kcal/mole). Thermodynamically, the only bond more stable is H-H. Hydrogen can attack the C-H surface bond to form H₂. No other atom is as effective. At elevated temperatures, other less thermodynamically stable bonds such as O-H or C-F can compete with C-H. It is believed that this temperature may be on the

order of 1000°C. (References for bond strengths are in the CRC Handbook of Chemistry and Physics, 70 th edition, page F-198.)

The surface finish of the diamond film must permit the transmission of the EXCITON produced U.V. photons so that losses can be minimized. Experimental evidence on the basis of hydrogen and krypton loaded samples indicates that transparency to visible and near-visible photons is preserved in diamond that has been processed by the forced diffusion method.

The density of the radioactive isotopes reaches a maximum when every interstitial void and every void in diamond crystal grain boundaries is filled by the atoms of the impregnated isotope. If only interstitial voids are considered, the density is equivalent to 829 atmospheres of tritium monoatomic gas or 138 atmospheres of diatomic molecular tritium gas at standard temperature, or 9.9 atmospheres of Kr-85 gas at standard temperature. This greater packing density provides an advantage over the Kr-85 battery concept of Prelas M. A., and Hora H. ("Efficient Nuclear Battery," German Patent # DE 43 00 225 A1 and US Patent Pending) which would require a pressure vessel capable of withstanding 60 to 100 atmospheres. The interstitially trapped isotope atoms cannot escape the very strong C-C covalent bonds at a significant rate unless the crystalline structure of the diamond is disrupted at temperatures greater than 1,000 degrees C. Therefore a

pressure vessel, together with the consequential design and qualification complexity, is not necessary. A containment vessel is likely to be a requirement to trap small amounts of decay product gases (H-3, He-3, Kr-85) which escape the lattice over decades of use; or even if just as a confidence building safety feature; or while the unit is on Earth. The forced diffusion method should be stable to temperature so the atomic density of the radioactive isotope should remain relatively constant with temperature up to a temperature where the diffusion coefficient becomes significant. Diffusion coefficients have a non-linear dependence on temperature.

In the preferred embodiment, as seen in Fig. 2, the diamond film is processed by means of the forced diffusion process, which is disclosed in U.S. Application S.N. 08/313,641 Entitled "Optical and Electrical Field Enhanced Diffusion of Impurities into Crystalline Materials," (filed on September 28, 1994 and naming as inventors G. Popovici, M. Prelas, T. Sung and S. Kasawinah) and is incorporated herein by reference, to impregnate small radioactive isotopes such as tritium or krypton-85. Tritium has a single electron and krypton has all of its electron shells completely filled and is therefore also small enough to occupy the interstitial void in diamond. The beta emission from a Kr-85 decay event has a factor 40 greater energy than the beta from tritium. This permits a lower loading

of Kr-85 into diamond for a comparable specific power. Experimental evidence gives confidence that the near theoretical interstitial packing by means of the forced diffusion process can be achieved.

5 Stress may be induced in the diamond crystal lattice by packing interstitial sites with atoms, by growing diamond on a material with a lattice mismatch, or by ion implantation (H. Hora, M. Prelas, "Theoretical Aspects of Diamond Film Laser Action," Diamond and related Materials, 4(12) 1378-1382
10 (1995)). A stress of about 4 Giga Pascal converts the diamond from an indirect band-gap to a direct band-gap material with a band-gap of about 4eV (W.Picket and Momehl, Micro-Optoelectronic Materials, SPIE, Vol. 877, 64 (1988)). The change to a direct band-gap material would allow photonic
15 transitions with photon emission of about 4 eV. A direct band gap transition is the most desirable method of producing photons. This is the mechanism used in photodiodes and semiconductor lasers, which are the most efficient fluorescence sources known today.

20 The spontaneous decay event of a nucleus of the radioactive isotope causes the emission of one beta or alpha particle before becoming the nucleus of another material. The beta or alpha particle will interact with the carbon atom electrons by the established mechanism of the EXCITON (B.E.A.

Saleh, M.C.Tech Fundamentals of Photonics, John Wiley and Sons, New York, 573-575 (1991)). This interaction yields a bound electron-hole pair within the crystal lattice.

When the electron-hole pair recombines, a photon with a
5 characteristic wavelength (and therefore energy) is emitted. In
diamond, the photons produced in this way have wavelengths of
either 235 nanometer (nm) or 242 nm, which are in the
ultraviolet region of the spectrum. In diamond of high quality
and low crystal lattice defects, EXCITON formation is virtually
10 100% efficient. The ultraviolet photons have a typical energy
of 5.1 electron volt.

Although the energy conversion mechanism known as EXCITONS
is exploited, it is noted that there are other processes that
could cause diamond to emit electromagnetic radiation in
15 response to charged particle irradiation. These mechanisms
include - colour centers, defects and vacancies (L.T. Lin,
M.A. Prelas, G. Popovici, "Laser Modes in Diamond", Wide Band-
Gap Electronic Materials, M.A. Prelas et. al. Editors, Kluwer
Academic Publishers, The Netherlands, 187-206 (1995)).
20 However, for an indirect band gap material such as diamond,
which has a bound EXCITON, the EXCITON mechanism is dominant.

Other than beta and alpha particles, as previously
described, gamma rays, x-rays and neutrons also can be products
of a decay in an isotope and can effect the release of photons,

although the mechanism is different. As is well known, beta particles, alpha particles and other ions interact with matter by Coulombic collisions. This mechanism is fundamentally different from gamma rays and neutrons. Gamma rays and x-rays
5 interact with matter by the photoelectric effect, Compton scattering, and pair production. X-rays are included because they are potential radioactive decay mechanisms that involve K level electrons. These mechanisms are different than beta particles, alpha particles, other ions and neutrons. Neutrons
10 interact with matter by elastic scattering, inelastic scattering, charged particle producing reactions, radiative capture and neutron multiplying reactions. These mechanisms are also different than beta particles, alpha particles, other ions and gamma rays. Nonetheless, all of these particles and
15 radiation types are capable of effecting the release of photons.

The conversion of the photon energy generated from the EXCITON mechanism to electric current can be achieved by photovoltaic cells. Highest energy conversion efficiency can be
20 achieved by the application of photovoltaic cells made of wide band-gap materials. Diamond based semiconductor or other wide band-gap material may be fabricated to produce such photocells that are optimized for a band-gap energy of 5.1 eV. Already

available low band-gap photocells can be used with a lower energy conversion efficiency.

Estimates indicate that the electron-hole pair production from tritium decay beta particles is about 70% efficient. This is because the photons produced by EXCITONs or direct band gap recombination have a very narrow bandwidth. In general, if the band gap is matched to narrow band width sources, the photovoltaic process approaches 100% efficiency. The fact that the spectra from the sun is broad bandwidth will explain why conventional solar cells are limited to 30% efficiency.

Since UV light production from EXCITON recombination is 100% and photovoltaic conversion of the light is 70%. The overall efficiency would be 49%. Holding the theoretical maximum of about 1×10^{23} tritium atoms per cubic centimeter, a beginning of life specific power of 27 Watts electric per kilogram could be obtained with this concept. An attractive specific power rating need only be 10 We/kg for practical applications.

The isotope-impregnated diamond films can be stacked to achieve a mass concentration of radioactive isotope that satisfies the "beginning of life" specified stored energy, as seen in Fig. 2. The assembly would necessarily be in a licensed radioactive handling facility. The methods for such handling and stacking are well known in the art. The stacking

method actually used will be governed by film flatness and warping characteristics. Ideally, the films will be undistorted and able to be laid one on top of the other. Distortions will cause unwanted gaps between the layers,

5 Microscopic unevenness of the films could occur even though the uniformity of the CVD films is very high. Residual gaps will be minimized by pressing the films together as part of the assembly procedure that will ensure a rigid structure of the stack of CVD radionuclide loaded films and photovoltaic films.

10 Retention devices in the form of screw down clamps may be used. An evacuation of the complete power cell sealed housing also may assist the close stacking.

The next step in the process is the installation of the photovoltaic cells, as seen in Fig. 2. The configuration of

15 the stack of radioisotope impregnated layers and the photovoltaic cell films is optimized to minimize the quantity of photocells. The diamond films impregnated with radioactive isotope atoms may be stacked between photovoltaic cell films of the same surface area in a worst case situation where the

20 EXCITON produced UV photon transmission is restricted or subject to absorption losses. A preferred configuration will stack the diamond films impregnated with radioactive isotope atoms into a block from which the UV photons will be emitted. Light collecting devices as well as photovoltaic cells,

mirrors, lenses and other optical equipment may be used to gather UV light and focus it onto photovoltaic cells, thus reducing the area of photovoltaic cells needed.

The photocells may be manufactured from substrate material that is of comparable film thickness to the EXCITON films. Such photocell films will have bi-directional sensitivity to incoming UV photons. The transparency to UV photons of the diamond films in which the decay and beta particle EXCITON reaction occurs is high so that the inefficiencies of the practical electric energy generation mechanism will be most apparent within the photocells. The manufacturing cost of the device will depend on the film area as is seen in semiconductor manufacturing of "wafers". Various configurations of the DEXRG device are possible, and the selection of the photocell and its operational constraints plus cost criteria will determine the overall configuration of the DEXRG device. An evolution of configuration will occur as the use of available photocells transitions to the use of diamond or other wide band gap semiconductor based photocells.

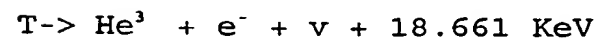
As seen in Figs. 3a, 3b, and 3c, the photocells would be affixed to the main surfaces parallel to the substrate layers, as these positions ensure access to the majority of the emitted photons. The photocells also can be affixed to the side faces

if UV photon transmission in those directions is at a significant level. The unused sides can be coated with a UV reflective material, using a conventional and compatible deposition process, many of which are known in the art. The reflective material will act to confine the emitted photons to the device and increase the number of emitted photons that actually pass through the photovoltaic cells. The blocks of loaded wafers may even have a "sandwich" structure where photovoltaic cells are inserted as every second or third layer.

The photocells covering the stacked diamond layers will be wired together and designs are available and are well known in the semiconductor industry may be used to connect the cells in parallel to achieve an optimal current collection bus array.

The DEXRG power cell will have a high concentration of tritium. Despite the low energy beta particle given off per decay 18.661 KeV, it is feasible to achieve a reasonable power per unit mass. Below is a calculation of the potential power per unit mass:

The half life for the reaction,



is 12.33 years, or in seconds:

$$\text{Half Life} = 12.33 \times 365 \times 24 \times 60 \times 60 = 3.88839 \times 10^8 \text{ seconds.}$$

The decay constant λ is:

$$\lambda = 0.693/\text{Half Life} = 1.78223 \cdot 10^{-9} \text{ (seconds)}^{-1}$$

A loading of one tritium to carbon is:

$$\text{Loading} = 1.76 \cdot 10^{23} \text{ Tritium Atoms/cc}$$

5 Activity, which is decays per second per cubic centimeter (cc),
is the loading times decay constant.

$$\text{Activity} = \text{Loading} \cdot \lambda = 3.13672 \cdot 10^{14} \text{ decays/(second - cc)}$$

The power density in the loaded diamond is the Activity x
the beta energy per decay. The beta energy per decay is 18,661
10 eV/3 (where 1/3 is the average weighting of beta energy) and
the conversion from eV to joules is 1.6×10^{-19} J/eV.

$$\text{Thermal Power Density} = \text{Activity} \cdot 18661 \cdot 1.6 \cdot 10^{-19} / 3 =$$

$$0.312183 \text{ W}_{\text{Th/cc}}$$

The electrical power density is the thermal power density x
15 electrical energy conversion efficiency x the ratio of the
thickness of the tritium loaded plate to the total thickness of
the tritium loaded plate (250 μm) and the photovoltaic cell (20
 μm).

$$\text{Electrical Power Density} = \text{Thermal Power Density}$$

$$20 \cdot 0.4 \cdot 250/270 = 0.115623 \text{ W}_{\text{e/cc}}$$

The volume per watt electric generated is the inverse of the Electrical Power Density.

$$\text{Volume}/W_e = 1/\text{Electrical Power Density} = 8.64876 \text{ cc}/W_e$$

The mass of one cubic centimeter (cc) of diamond is:

5 $\text{Mass one cc of Diamond} = 0.0035 \text{ kg}$

The watts of electricity produced per one kg of diamond is:

$$\text{Watts Electric Per kg} = 1/(\text{Volume} / W_e * \text{Mass one cc of Diamond}) = 33.0353 W_e/\text{kg}$$

10 This calculation is for the unit ratio of one tritium atom to one carbon atom. To find the watts electric per kg for a specific case, multiply the ratio of tritium atoms to carbon atoms by 33.0353.

15 The use of phosphors or wavelength shifting media to convert the emitted UV to a frequency better suited to the available photovoltaic cells in use is also a design option.

20 Inefficiency will be apparent as waste heat. The steady-state temperature of the DEXRG device will depend on the quantity of radioactive material and its activity. With a typical overall efficiency of, for example, 25% a 500 Watt electricity production would be accompanied by 1500 Watts of thermal power. A passive heat radiation scheme would attain a steady-state temperature in the region of 400 degrees C. Since

diamond is an excellent thermal conductor, heat paths may be built into the device by coupling the outer perimeter of the films to a conductor integrated into the wall structure.

As a radioisotope based power source the DEXRG will
5 always be an active generator of electric and thermal power. Its performance profile will be determined by the combination of radioactive half life (13 - 10.7 years for tritium and krypton-85) and degradation of efficiency of the photovoltaic cells; particularly photovoltaic cells made of semiconductor
10 substrates other than diamond. A single diamond semiconductor photocell of a few square centimeter collection surface area could operate with the entire UV photon flux of the reference 500 Watt electric device without experiencing saturation related limitations from the photon flux or thermal flux. The
15 use of stressing, doping or combining (sandwiching) semi-conducting materials to achieve a photovoltaic cell with a particular band-gap value may be a design option.

The thermal energy may also be partially converted to electric current by means of various conversion devices that
20 can be installed in the heat flow paths of a device using the diamond lattice containment method.

A non-pressurized containment structure is necessary for several reasons. In the case of Kr-85, there is a gamma radiation hazard arising from the decay product Rubidium -85 in

some decay events. Shielding is required against this high energy (514 keV) gamma radiation. The high packing density described above offers the advantage of a more compact power source with a corresponding reduction of surface area for shielding material. In the case of the tritium based device, there is no gamma or other hazardous radiation that can penetrate a minimal protective structure or casing.

The containment vessel must be designed to provide protection against the escape of gas as well as radiation shielding. Further, it must provide protection of the DEXRG from handling damage, yet must offer an ability to structurally attach the device to application systems, such as spacecraft, aircraft, submersible vehicles, surface vehicles or static equipment. Where conditions are severe, such as spacecraft atmospheric reentry where high altitude destructive burn-up is preferable to crash landing survival, the packaging can be designed to ensure achievement of such goal.

An illustration of a typical DEXRG device, including attachment structures and wiring, is seen in Fig. 4. The ultimate dimensions of a power cell will be determined by the radioactive isotope packing density that can be practically or cost effectively achieved, the overall energy conversion efficiency and the specified beginning of operational life electrical output. The technology development goals will be

defined to achieve as high an energy packing density as possible.

Disposal of the device at the end of its useful life will not require disassembly or removal of waste material. The
5 entrapment of the residual radioactive isotope and the decay product atoms within the diamond crystal lattice will be similar to glass encasement of radioactive waste. The extraction of the residual tritium would be a very difficult process and not conducive to nuclear material proliferation.

10 Accidental loss or damage of the device will not easily cause a release of hazardous radioactive material. Even in an extreme accident scenario where release may occur, the escape of Kr-85 into the atmosphere in the amounts involved is permissible under present regulations governing the nuclear
15 industry. A tritium release scenario would involve very high temperatures, as noted above, with consequential rapid dispersal via many chemical reactions and atmospheric dissipation.

Not only does the DEXRG offer technical advantages but it
20 offers a plausible solution to the use of safer alternative radionuclide energy sources in electricity and heat production applications where there are no other politically acceptable alternative technologies.